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Influence of ageing process on porosity changes of the external plasters

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Abstract

In recent time more and more attention has been paid to the durability problems of building materials and components. The key issue in this area is to define the service life. Therefore, useful methods for durability valuation are of prime importance. In the paper we present a method to define an acceleration ageing coefficient involving naturally and simulate degradation of external mineral plasters. To reach the above objective, elements of the kinetics process theory used in chemistry and power engineering have been adopted for the description of changes in pore-capillary materials. The emphasis has been placed on open capillary porosity, which was examined over time by mercury porosimetry method. Plasters were exposed to ageing processes in the natural and an artificial environments. Basing on that, the porosity changes in plasters in both environments and their mutual relation were studied. An acceleration coefficient of ageing process has been established, which can be used for durability assessment on the grounds of a short laboratory test.

Keywords: External plasters; Natural and simulate ageing processes; Capillary porosity

1. Introduction

External plasters are still widely used for facade materials. It protects the external walls from the destructive influence of weathering agents and architectural appearance. An aesthetic function is connected with visible defects on the facade surface, such as: dirting, crazing, cracking and separation of plaster from the background, sometimes falling down [1]. Most of these durability problems occur by weathering factors, different physical properties of plaster and background as well as bad workmanship.

Usually plasters are subjected to complex atmospheric factors, such as: temperature changes (especially low temperature and changes around 0 °C), moisture, solar radiation, rain, wind and atmospheric gases (Figs. 1 and 2). These variations bring physical and chemical changes leading to the deterioration of plaster layer [2–4].

Temperature and humidity gradients can cause deformations leading to tensions and stresses. Shrinkage and expansion result in the decrease of adhesion between rendering and background [1]. The leaching of alkaline binder results in decrease strength and bulk density, loss of mass, increase of total porosity and variations in pore structure.

These negative effects can be aggravated by the rise of ice during freezing and crystallisation of salts. All these phenomena form the ageing process and have influence on the durability of facade plasters during service life.

The complexity of weather factors together with the phenomena specified above make it difficult to valuate the durability. To simplify the problem, the emphasis

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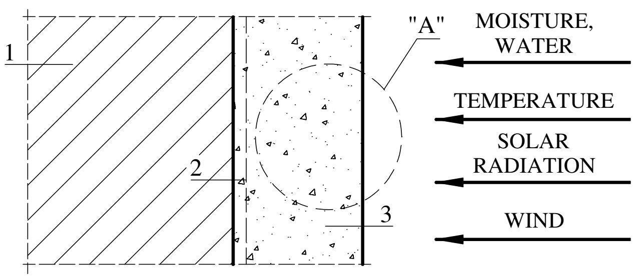

1- background, 2 - contact surface, 3 - plaster layer

Fig. 1. Scheme of weathering agents on external plaster.

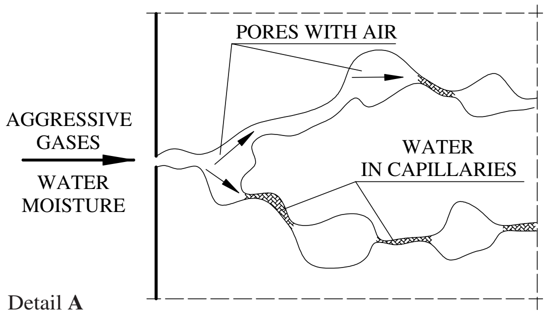

Fig. 2. Influence of pore structure of plaster on the penetration of atmospheric gases and moisture [9].

has been placed on the properties being essential for durability. The properties in question involve such factors as porosity and pore structure, which has been confirmed by Neville [8] and other investigators [7,9], who believe that the tightness of material structure is of fundamental importance in terms of the penetration effected by water and gases. These parameters substantially influence the strength [5], density, sorptivity [10], capillary suction, absorption [6], permeability [7] and frost resistance [4,10], which are applied in durability prediction methods of building materials [9,10].

In view of the above, the porosity and pore structure variations during ageing processes can be useful in terms of ageing and durability studies, especially when there is no method for the evaluation of durability of external plasters. Therefore, investigations have been carried out on the porosity variations of mineral facade plasters subjected to the natural and accelerated ageing tests, as recommended by the durability procedures [11,12]. Having compared the obtained changes in the examined plasters, we can define an acceleration coefficient between the natural and simulate ageing, which is required for durability prediction [13].

2. Methodology of research

For the ageing tests four types of mortars mixtures were prepared (Table 1). Two ordinary mortars: with cement and cement–lime as binder, and two thin-layer types made of modified mixtures with the additions: cement–lime Y (Ytong system) and cement E (Euromix system). Plasters were prepared to achieve class M3. Modified mortars were prepared in accordance with the manufacturers' recommendation.

All mortar samples were cast into 16 prisms of the size $4 \times 14 \times 16$ cm and next they were subjected to the prolonged ageing test in the natural environment on

Fig. 3. The PAT stand for natural ageing test.

Table 1
Composition of mortars

Type of mortar	C:L:S	Mortar class	Strength (MPa)	Cement (g)	Lime (g)	Sand (g)	Water (ml)
Cement	1:0:6	M3	10.21	425	–	2550	480
Cement–lime	1:1:6	M3	5.84	225	225	1350	315
Cement–lime Y	0:1:5	M1.5	1.73		435	1365	450
Cement E	1:0:5	M3	7.80	420	–	1680	520

Fig. 4. Samples of plasters in the CAT stand.

the PAT stand (Prolonged Ageing Test) for 8 years since 1994–2001 (Fig. 3).

During this time the above mortar samples were placed in the CAT chamber (Chamber Ageing Test) [13] and subjected to the accelerated ageing test (Fig. 4).

The chamber generates artificial conditions, such as: solar and ultraviolet radiation, heating to the temperature +60 °C, water spray together with gusts of air, freezing to −20 °C. These climates are produced by the simulate climatic chamber (Fig. 5). Three of such chambers works simultaneously together with the central one, which makes a 90° turn every hour. One side of the central chamber is free and is subjected to laboratory temperature of about 18 °C.

In this way, the mortar samples in the CAT stand, are alternately exposed to all climatic conditions during 4-h cycles. It gives altogether 5 cycles per day and 100 cycles per month. The stand has automatic and remote control by a computer. All climate parameters can be specified optionally. Samples were placed on the central chamber walls (Fig. 4) on different backgrounds: concrete, ceramic, cellular concrete and styrofoam and then subjected to simulated climates during 3 × 100 cycles.

Main emphasis was given to porosity and pore structure variations during the ageing tests. After particular time, the pore structure of samples from both environments was examined by a mercury porosimetry method [14,15] on the apparatus Carlo Erba 2000, within the pressure range 0.1–200 MPa and pore size

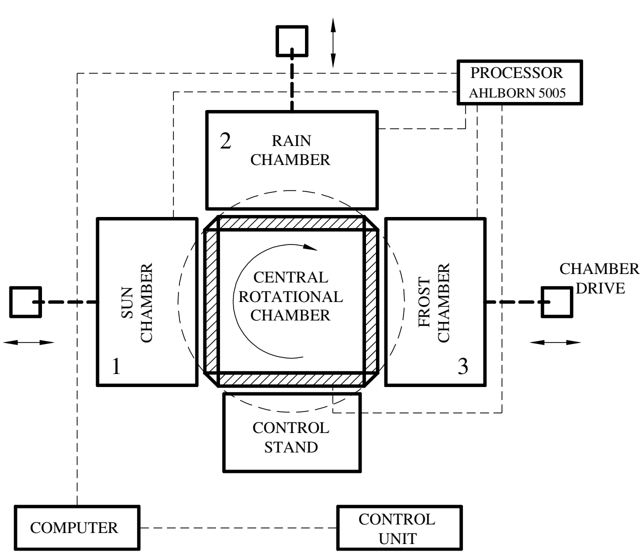

Fig. 5. CAT stand scheme for accelerated ageing test.

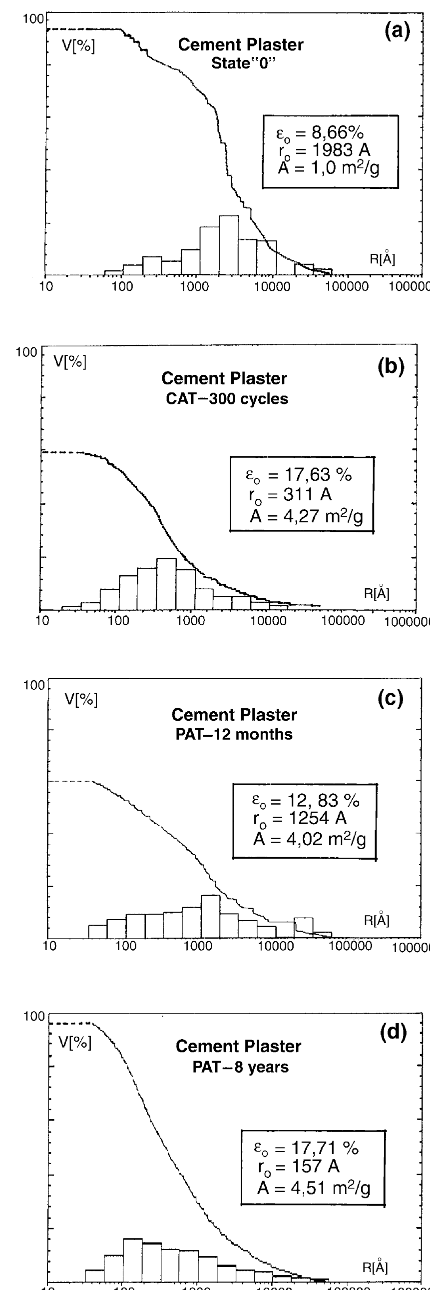

Fig. 6. Changes of pore structure with an average pore size, r'_0 of cement plaster during ageing process.

Table 2
Porosity changes of mortar samples in the PAT stand in natural environment

Type of mortar		Total porosity changes Δε (%)				
		State 0	1 year	2 years	5 years	8 years
Cement	nC	8.66	12.83	14.91	16.47	17.71
Cement–lime	nCL	10.14	13.94	15.21	17.48	19.32
Cement–lime Y	nLY	8.71	11.62	13.87	15.20	17.44
Cement E	nCE	8.55	9.73	10.87	13.08	15.05

Table 3
Porosity changes of mortar samples in the CAT chamber exposed to simulate environment

Type of mortar		Total porosity changes Δε (%)			
		State 0	100 cycles	200 cycles	300 cycles
Cement	sC	8.66	11.46	12.25	17.63
Cement–lime	sCL	10.14	12.38	15.46	19.76
Cement–lime Y	sLY	8.71	11.65	12.21	16.94
Cement E	sCE	8.55	10.14	12.19	16.32
Cement E + Ahydrosil	sCEA	10.76	12.01	14.21	17.46

3.8–7500 nm. The results showed that there is an evident influence of the ageing processes on pore structure. A range of pores with average pore size was decreasing over time towards less diameters (Fig. 6).

Simultaneously a total porosity was increasing (Tables 2 and 3). The results have been used to work out a model based on obtained porosity changes.

3. Kinetic equation of porosity evolution

The results presented above, have been used for calculating the kinetic porosity model based on the changes of capillary pore volume. For this, elements of kinetics process theory have been adopted [16,17]. This approach is usually used for the description of fast chemical or power engineering processes. With certain assumptions, it can be adapted to slow processes, such as outgassing of coal and coke. In view of this, a kinetic equation is proposed for the modelling of open porosity increase (Eq. (1)).

$$\frac{\mathrm{d}\Delta\varepsilon(t)}{\mathrm{d}t} = \sum_{j=1}^{J} k_{0j} \exp\left(-\frac{E_j}{RT}\right)\left(\Delta\varepsilon_{\infty j} - \Delta\varepsilon(t)\right) \qquad (1)$$

where $\Delta\varepsilon(t)$, increase of total porosity in time "t", %; k_{0j}, pre-exponential factor of "j" reaction-sequence, s^{-1}; E_j, activation energy of "j" reaction-sequence, kJ/mol; $\Delta\varepsilon_{\infty j}$, porosity increase of "$j$" sequence for time $t = \infty$, %; R, gas constant, kJ mol^{-1} K^{-1}.

For the ageing of mortar samples within the narrow range of temperature (253–293 K), which has insignificant influence on the speed of the ageing process, an isothermal process has been assumed. The solution of Eq. (1) was found by integrating the expression with T = constant, from the initial time $t = 0$ to the final time $t = \zeta$ and initial increase of porosity $\Delta\varepsilon(0) = 0$ to the final increase $\Delta\varepsilon(\zeta) = \Delta\varepsilon_{\zeta}$. After the integration, the model curves were determined on the basis of the Eq. (2) (Figs. 7 and 8). The quantity J in the equations, expresses the sequences of total porosity increase.

$$\Delta\varepsilon(t) = \sum_{j=1}^{J} \Delta\varepsilon_{\infty j}\left(1 - \exp\left(-k_{0j}\cdot\exp\left(\frac{-E_j}{RT}\right)\cdot t\right)\right) \qquad (2)$$

The expression (2) was applied in the modelling of porosity changes in mortar samples in two climatic environments—natural and artificial. The correlation between these environments, based on the above equation, makes it possible to assessment the porosity variations in time.

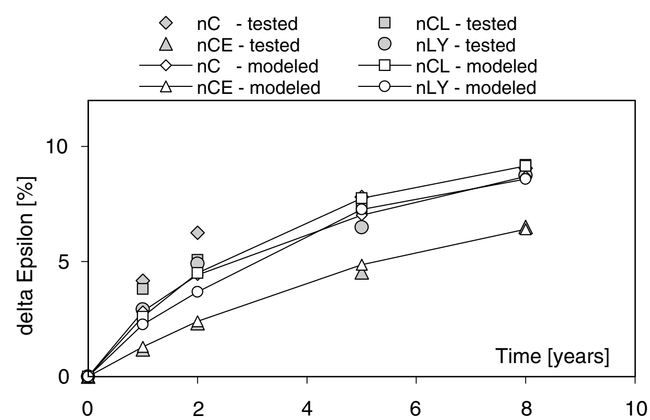

Fig. 7. Measured and modeled total porosity variations of plasters during natural ageing process.

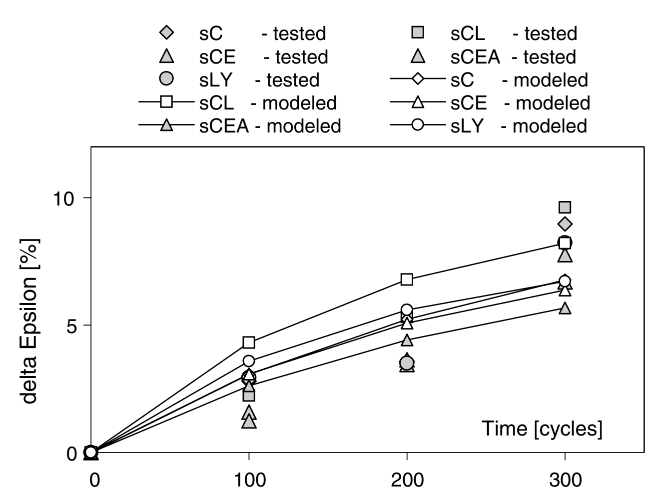

Fig. 8. Examined and modeled total porosity variations of plasters during simulate ageing process.

4. Changes of porosity in the natural ageing

For the description of the increments of porosity in natural conditions (PAT) by the multisequenced equation (2), the average value of the long-term temperature 280.8 K for Silesian region from 1970 to 2000 was used, according to statistical data from The Meteorology Institute in Katowice. The kinetic constants k_{0j}, E_j and $\Delta\varepsilon_{\infty j}$ for jth equation, were determined basing on the experimental results for the four mortars samples (Table 4). The best set of kinetic constants was found from the expression (3) of the value of minimum sum for three conditions as below.

$$S = \sum_{i=1}^{I} \left[\frac{\varepsilon_i - \varepsilon_{i-1}}{\Delta t_i} - \left. \frac{d\varepsilon(t)}{dt} \right|_i \right]^2 = \min \tag{3}$$

$$\frac{\partial S}{\partial k_{0j}} = 0, \quad \frac{\partial S}{\partial E_j} = 0, \quad \frac{\partial S}{\partial \varepsilon_{\infty j}} = 0.$$

Three equations were sufficient to obtain a reasonable correlation with the values of 0.981–0.998 by Mathcad programme. The plotted results of Eq. (2) provide the modeled curves of porosity increments (Fig. 7). The model provides quite an accurate simulation of porosity changes in the four mortars during the prolonged ageing test. The same analysis was carried out for the results of accelerated ageing.

5. Changes of porosity in the accelerated ageing process

For the estimation of the porosity changes in mortars subjected to the accelerated ageing in a simulated environment, the analogous calculation model has been applied. The tests were carried out on mortar samples. One of them was covered with a hydrophobic coating of Ahydrosil, a solution of methylosilicone resin. Eq. (2) describes porosity changes in the chamber's environment related to the number of testing cycles. The average temperature taken from the thermal characteristics for one cycle in the CAT stand is 295 K [13]. The increase of the porosity in the following stages of the ageing processes was determined by porosimetry measurements (Table 3). The porosity increase for infinite time ($t \to \infty$) was estimated basing on the measurements of a facade mortar of the building erected in 1934 in Katowice, for which the mean total porosity was 22.8%. For the three equations in expression (2) the correlation of experimental results with model data was good enough, with the values of 0.887–0.957. The calculated kinetic constants (Table 5) allowed us to reproduce the porosity changes for each mortar, yielding in effect, five graphs (Fig. 8).

Finally, two different characteristics of porosity changes in two environments (PAT, CAT) were obtained for each mortar (Figs. 7 and 8). The differences between each pair of the curves raise a question, what relationship the curves have and what applicability potentials they offer for durability prediction.

6. Application of kinetics of porosity changes for prediction

Having two kinds of characteristics for each plaster, which describe kinetic changes of capillary porosity in the natural and a simulated environment, it is possible to find a mutual relation between them. The correlation

Table 4
Kinetic constants of total porosity evolution for natural ageing process

Type of mortar		Eq. (1)			Eq. (2)			Eq. (3)		
		k_{01} (s^{-1})	E_1 (kJ/mol)	$\Delta\varepsilon_{\infty j}$ (%)	k_{02} (s^{-1})	E_2 (kJ/mol)	$\Delta\varepsilon_{\infty j}$ (%)	k_{03} (s^{-1})	E_3 (kJ/mol)	$\Delta\varepsilon_{\infty j}$ (%)
Cement	nC	5.5×10^4	29.0	3.0	3.7×10^5	30.0	7.0	1.3×10^{12}	71.0	8.0
Cement–lime	nCL	1.7×10^2	39.0	3.0	4.5×10^8	54.0	5.0	1.2×10^{13}	73.0	9.0
Cement–lime Y	nLY	1.7×10^{12}	55.0	4.0	6.9×10^7	56.0	5.0	1.6×10^{11}	63.0	9.0
Cement E	nCE	1.7×10^2	55.0	4.0	6.5×10^7	60.0	5.0	0.8×10^{11}	63.0	9.0

Table 5
Kinetic constants of total porosity evolution for simulate ageing process

Kind of mortar		Eq. (1)			Eq. (2)			Eq. (3)		
		k_{01} (s^{-1})	E_1 (kJ/mol)	$\Delta\varepsilon_{\infty j}$ (%)	k_{02} (s^{-1})	E_2 (kJ/mol)	$\Delta\varepsilon_{\infty j}$ (%)	k_{03} (s^{-1})	E_3 (kJ/mol)	$\Delta\varepsilon_{\infty j}$ (%)
Cement	sC	1.7×10^2	29.0	4.0	1.9×10^4	65.0	6.0	3.5×10^{10}	73.0	8.0
Cement–lime	sCL	1.1×10	29.0	3.0	9.9×10^3	58.0	5.0	2.2×10^{10}	71.0	10.0
Lime–lime Y	sLY	1.1×10	29.0	4.0	9.9×10^3	52.0	6.0	2.3×10^{10}	71.0	8.0
Cement E	sCE	1.1×10	29.0	4.0	6.9×10^3	42.0	6.0	0.8×10^{10}	69.0	8.0
Cement E + A	sCEA	2.5×10^1	29.0	4.0	2.9×10^3	50.0	5.0	1.5×10^{10}	71.0	8.0

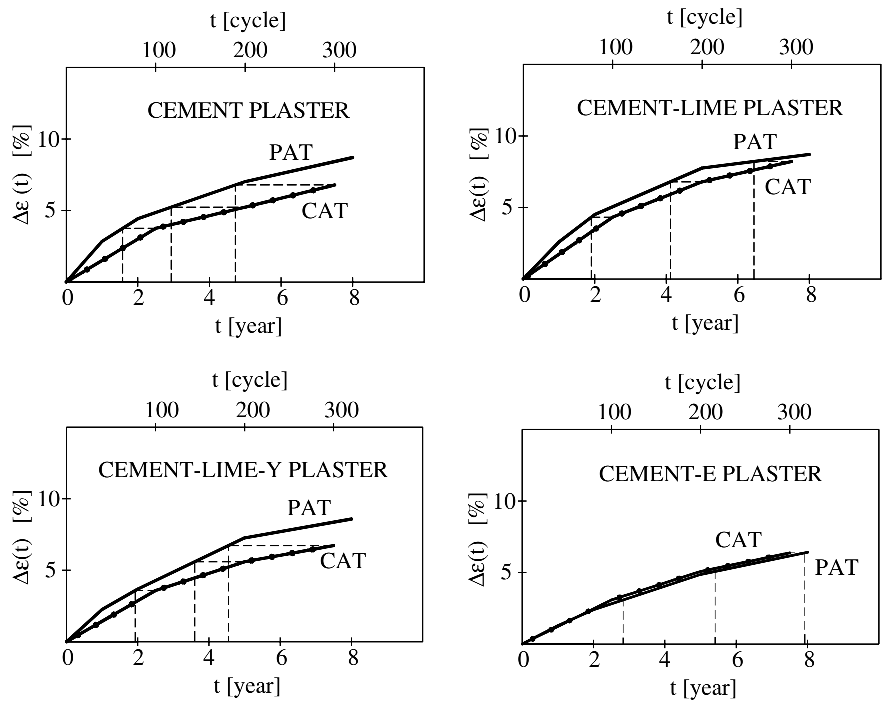

Fig. 9. Relations between times in CAT test and PAT test for facade plasters.

Table 6
Valuation of real time on the basis of curve comparison of porosity increase in simulate and natural environment

Type of mortar	Value of modeled "Δε" in CAT (%)			Corresponding real time in PAT (years)				Acceleration CAT:PAT
	100c	200c	300c	100c	200c	300c	Average/100c	
Cement	3.07	5.23	6.78	1.5	3.0	4.7	1.5	18:1
Cement–lime	4.32	6.79	8.21	1.9	4.1	6.4	2.0	24:1
Cement–lime Y	3.58	5.59	6.72	2.0	3.6	4.5	1.8	22:1
Cement E	3.08	5.07	6.37	2.7	5.4	8.0	2.7	32:1

could be applied for the prediction of porosity changes of facade materials in time. It could be useful for durability prediction of external plasters. On the basis of the resultant curves (Fig. 9) it can be seen, that the increments of total porosity are different for each mortar. It denotes different answers of their structure to ageing influences. Furthermore, the answers are different with respect to natural (PAT) and simulate (CAT) ageing processes. By transferring the values of porosity increments from the accelerated ageing curves to the natural ageing graphs (Fig. 9), we have information what real time in the natural conditions PAT corresponds to 100, 200 and 300 cycles in the simulate environment CAT (Fig. 9, Table 6).

In view of the above, an average real time, corresponding to 100 cycles of simulate ageing, can be valuated for each plaster. Since 100 cycles of accelerated test takes 1 month [13], and the acceleration coefficient of CAT ageing to PAT stand is 18–32, depending on the kind of mortar (Table 6), so the predicted real time is 1.5–2.7 years per 100 cycles. Having determined this relation, it is possible to predict the changes of porosity in the natural environment basing on the variations obtained from the accelerated ageing test. Such a method can be applied for the prediction of durability.

7. Conclusions

1. The influence of different atmospherics on facade resulted in variations of pore structure, both in natural and simulate environments. Average pore size decreases with time, but the volume of open porosity increases. These phenomena confirm the tightness of the binder's structure and its leaching as well.
2. The natural and accelerated ageing tests brought about the increase of porosity in time between 6.50% and 9.62%. These changes can be described by the kinetic equation of open porosity increments in time. This description offers a good approximation of pore transformation inside a structure of mortars with the correlation of 0.887–0.998.

3. By comparison of model graphs of mortars porosity from the natural environment to the curves from the accelerated test, time relations between the two ageing processes is obtained. In view of that, real time corresponding to cycle time of simulate ageing can be determined for each mortar. The acceleration coefficient of the simulate to natural test is 18–32, depending on the kind of plaster, and denotes the relation of 1.5–2.7 years per 100 cycles. Making use of these relationships the porosity changes in the natural weathering can be predicted on the basis of a short-time lab test. This approach can be applied for the durability prediction of external plasters.

References

[1] How Son L, Yuen G. Building maintenance technology. London: Macmillan Press Ltd.; 1993.

[2] Matsufui Y, Koyama T, Harada S. Service life predictive method of building materials. In: Seventh international conference on durability of building materials and components, vol. 1. Sweden; 1996. p. 45–53.

[3] Meyer A. The importance of the surface layer for the durability of concrete structures. In: Katherine, Bryant Mather, editors. International conference on concrete durability, Atlanta, USA; 1987. p. 48–61.

[4] Pigeon M, Talbot C, Marchand J, Hornain H. Surface microstructure and scaling resistance of concrete. Cem Concr Res 1996;26(10):1555–65.

[5] Rößler M, Odler I. Investigations on the relationship between porosity, structure and strength of hydrated Portland cement pastes. Part I and II. Cem Concr Res 1985;15. p. 320 and 401.

[6] Martys N, Ferraris C. Capillary transport in mortars and concrete. Cem Concr Res 1997;27(5):747–60.

[7] Bagel L, Zivica V. Relationship between pore structure and permeability of hardened cement mortars, on the choice of effective pore structure parameter. Cem Concr Res 1997;27(8):1225.

[8] Neville A. Properties of concrete. 4th ed. Arkady, Kraków; 2000 [in Polish].

[9] Fagerlund G. Moisture mechanics as a tool for service life prediction. In: Sjöstrom C, editor. Seventh international conference on durability of building materials and components, vol. 1. Sweden; 1996. p. 21–31.

[10] Fagerlund G. Assessment of the service life of materials exposed to frost. In: Seventh international conference on durability of building materials and components, vol. 1. Sweden; 1996. p. 34–44.

[11] BS ISO 15686-2/2001. Buildings and constructed assets—service life planning. Part 2. Service life prediction procedures.

[12] Martinez-Ramirez S, Puertas F, Blanco-Varela M, Thompson G. Studies on degradation of lime mortars in atmospheric simulation chambers. Cem Concr Res 1997;27(5):777–84.

[13] Bochen J, Nowak H, Andreasik M. Beschleunigte Alterungstests von Aussenputzen zur Prognose der Dauerhaftigkeit. In: Fifth international colloquium 'Materials Science and Restoration 99', Esslingen, Germany; 1999.

[14] Laskar A, Kumar R, Bhattacharjee B. Some aspects of evaluation of concrete through mercury intrusion porosimetry. Cem Concr Res 1997;27(1):93.

[15] Cook R, Hover K. Mercury porosimetry of hardened cement pastes. Cem Concr Res 1999;29:933–43.

[16] Tomeczek J, Gil S. Kinetics of porosity evolution during fast heating of coal. In: Eighth international conference on coal science, Oviedo; 1995. p. 925–8.

[17] Tomeczek J, Gil S. Volatiles release and porosity evolution during high pressure coal pyrolysis. Fuel 2003;82:285–92.